AFRL-AFOSR-VA-TR-2016-0206

A Comprehensive Theory of Algorithms for Wireless Networks and Mobile Systems

Nancy Lynch
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

06/08/2016
Final Report

Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/ RTA2
Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE	2. REPORT TYPE:	3. DATES COVERED
06/07/16	Final	*04/13-05/16*

4. TITLE AND SUBTITLE

A Comprehensive Theory of Algorithms for Wireless Networks and Mobile Systems

5a. CONTRACT NUMBER: FA9550-13-1-0042

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR:

Nancy Lynch

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES):

MIT, 77 Massachusetts Avenue, Cambridge, MA 02139-4301

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES):

Beth Snyder, Office of Naval Research (BD242, Room 368), 875 N. Randolph Street, Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM:

ONR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT:

Approved for public release. Distributed is unlimited

13. SUPPLEMENTARY NOTES:

NONE

14.ABSTRACT:

This project has produced many new algorithms and some lower-bound results for ad hoc wireless network models, and has also developed abstraction layers that are intended to make it easier to algorithms and applications for wireless networks. Since some of the results can be expressed in terms of abstract graph networks, the project has also produced many new graph network algorithms. Other results involve distributed data management and biology-inspired distributed algorithms. More specifically, the project has produced efficient algorithms for both reliable and unreliable radio network wireless platform models, for the rudimentary Beeping model, and for the Signal-to-Noise-and-Interference (SINR) model. These algorithms have solved such problems as local and global broadcast, computing a Maximal Independent Set, and establishing other network structures. The project has developed an Abstract MAC (Local Broadcast) abstraction layer, with efficient implementations over several different wireless platform models, based on reasonable constraints on network geometry. The project has also produced new graph network algorithms for graph connectivity problems, distance computations, coloring, Maximal Independent Set, and various forms of spanning trees. Finally, it has produced an interesting method for running several distributed algorithms concurrently, in the same graph-based network. This work has resulted in six Best Paper and Best Student Paper awards.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF: U			17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE	UU		Joanne Hanley
					19b. TELEPHONE NUMBER 617-253-6054

Reset

INSTRUCTIONS FOR COMPLETING SF 298

1. REPORT DATE. Full publication date, including day, month, if available. Must cite at least the year and be Year 2000 compliant, e.g. 30-06-1998; xx-06-1998; xx-xx-1998.

2. REPORT TYPE. State the type of report, such as final, technical, interim, memorandum, master's thesis, progress, quarterly, research, special, group study, etc.

3. DATES COVERED. Indicate the time during which the work was performed and the report was written, e.g., Jun 1997 - Jun 1998; 1-10 Jun 1996; May - Nov 1998; Nov 1998.

4. TITLE. Enter title and subtitle with volume number and part number, if applicable. On classified documents, enter the title classification in parentheses.

5a. CONTRACT NUMBER. Enter all contract numbers as they appear in the report, e.g. F33615-86-C-5169.

5b. GRANT NUMBER. Enter all grant numbers as they appear in the report, e.g. AFOSR-82-1234.

5c. PROGRAM ELEMENT NUMBER. Enter all program element numbers as they appear in the report, e.g. 61101A.

5d. PROJECT NUMBER. Enter all project numbers as they appear in the report, e.g. 1F665702D1257; ILIR.

5e. TASK NUMBER. Enter all task numbers as they appear in the report, e.g. 05; RF0330201; T4112.

5f. WORK UNIT NUMBER. Enter all work unit numbers as they appear in the report, e.g. 001; AFAPL30480105.

6. AUTHOR(S). Enter name(s) of person(s) responsible for writing the report, performing the research, or credited with the content of the report. The form of entry is the last name, first name, middle initial, and additional qualifiers separated by commas, e.g. Smith, Richard, J, Jr.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES). Self-explanatory.

8. PERFORMING ORGANIZATION REPORT NUMBER. Enter all unique alphanumeric report numbers assigned by the performing organization, e.g. BRL-1234; AFWL-TR-85-4017-Vol-21-PT-2.

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES). Enter the name and address of the organization(s) financially responsible for and monitoring the work.

10. SPONSOR/MONITOR'S ACRONYM(S). Enter, if available, e.g. BRL, ARDEC, NADC.

11. SPONSOR/MONITOR'S REPORT NUMBER(S). Enter report number as assigned by the sponsoring/ monitoring agency, if available, e.g. BRL-TR-829; -215.

12. DISTRIBUTION/AVAILABILITY STATEMENT. Use agency-mandated availability statements to indicate the public availability or distribution limitations of the report. If additional limitations/ restrictions or special markings are indicated, follow agency authorization procedures, e.g. RD/FRD, PROPIN, ITAR, etc. Include copyright information.

13. SUPPLEMENTARY NOTES. Enter information not included elsewhere such as: prepared in cooperation with; translation of; report supersedes; old edition number, etc.

14. ABSTRACT. A brief (approximately 200 words) factual summary of the most significant information.

15. SUBJECT TERMS. Key words or phrases identifying major concepts in the report.

16. SECURITY CLASSIFICATION. Enter security classification in accordance with security classification regulations, e.g. U, C, S, etc. If this form contains classified information, stamp classification level on the top and bottom of this page.

17. LIMITATION OF ABSTRACT. This block must be completed to assign a distribution limitation to the abstract. Enter UU (Unclassified Unlimited) or SAR (Same as Report). An entry in this block is necessary if the abstract is to be limited.

Final Report for AFOSR Contract FA9550-13-1-0042: A Comprehensive Theory of Algorithms for Wireless Networks and Mobile Systems

This report has two sections: an incremental report for the final year, followed by a summary of accomplishments for the entire contract.

1 Incremental Report for April 1, 2015—May 31, 2016

The core topics of the project are algorithms and abstraction layers for wireless network algorithms. In the course of the project, we have learned that many key ideas for wireless network algorithms can be expressed in more abstract graph-theoretic terms, and so, we have developed many of our algorithms in terms of such models. We also have new coding-based algorithms for efficient distributed data management in fault-prone distributed networks. Finally, we have designed new distributed algorithms related to biological systems, which suggest new ways of designing new, more adaptive algorithms for wireless networks.

1.1 Wireless Network Algorithms

In papers [1]-[3] below, we have developed new, efficient implementations of Local Broadcast abstraction layers (also known as Abstract MAC layer) for two important and well-studied types of wireless network platforms: unreliable radio networks and Signal-to-Noise-and-Interference (SINR) platforms. A highlight of this work is that efficiency is assessed in terms of local parameters only.

[1] Nancy Lynch and Calvin Newport. A (Truly) Local Broadcast Layer for Unreliable Radio Networks. Technical Report MIT-CSAIL-TR-016, Computer Science and Artificial Intelligence Laboratory, Massachusetts Institute of Technology, Cambridge, MA 02139, May 2015.

[2] Nancy Lynch and Calvin Newport. A (Truly) Local Broadcast Layer for Unreliable Radio Networks. ACM Symposium on Principles of Distributed Computing (PODC 2015), Donostia-San Sebastian, Spain, pages 109-118, July 2015.

[3] Magnus Halldorsson, Stephan Holzer and Nancy Lynch. A Local Broadcast Layer for the SINR Network Model. ACM Symposium on Principles of Distributed Computing (PODC 2015), Donostia-San Sebastian, Spain, pages 129-138, July 2015. http://www.arxiv.org/abs/1505.04514.

We have also developed a new leader-election algorithm for unreliable radio networks:

[4] Mohsen Ghaffari and Calvin Newport. Leader Election in Unreliable Radio Networks. To appear in International Colloquium on Automata, Languages, and Programming (ICALP), Rome Italy, July 2016.

Papers [5]-[7] below contain interesting new techniques for solving local and global communication problems over wireless networks that support network coding:

[5] Keren Censor-Hillel, Bernhard Haeupler, Nancy Lynch, and Muriel Medard. Bounded-Contention Coding for the Additive Network Model. Distributed Computing, 28(5):297-308, 2015.

[6] Keren Censor-Hillel, Erez Kantor, Nancy Lynch, and Merav Parter. Computing in Additive Networks with Bounded-Information Codes. Submitted for journal publication, 2016.

[7] Keren Censor-Hillel, Erez Kantor, Nancy Lynch, and Merav Parter. Computing in Additive Networks with Bounded-Information Codes. In Yoram Moses, editor, Distributed Computing: 29th International Symposium (DISC 2015), Tokyo Japan, October 2015, volume 9363 of Lecture Notes in Computer Science, pages 405-519, 2015. Springer.

The following papers are all currently "submitted for publication". Paper [8] and [9] determine costs of communication in wireless networks with multiple channels, and with "oblivious" adversarial scheduling. Paper [10] presents a new algorithm for fault-tolerant leader election in the SINR model. Paper [11] is a preliminary announcement of an extremely efficient new algorithm for computing a Maximal Independent Set, when only simple "beep" communication is available.

[8] Stephan Holzer, Thomas Locher, Yvonne Anne Pignolet and Roger Wattenhofer. Deterministic Multi-Channel Information Exchange. Submitted for journal publication, 2014.

[9] Magnus Halldorsson, Stephan Holzer, Pradipta Mitra and Roger Wattenhofer. The Power of Oblivious Wireless Power. Submitted for journal publication, 2015.

[10] Stephan Holzer and Evangelia Anna Markatou. Brief Announcement - Leader Election in the SINR Model with Stopping Failures. Submitted for publication, 2016.

[11] Stephan Holzer and Nancy Lynch. Brief Announcement - Beeping a Maximal Independent Set Fast. Submitted for publication, 2016.

The following papers [12]-[14] describe communication patterns for SINR wireless models.

[12] Erez Kantor, Zvi Lotker, Merav Parter and David Peleg. Nonuniform SINR+Voronoi Diagrams are Effectively Uniform. In Yoram Moses, editor, Distributed Computing: 29th International Symposium (DISC 2015), Tokyo Japan, October 2015, volume 9363 of Lecture Notes in Computer Science, pages 588-601, 2015. Springer.

[13] Erez Kantor, Zvi Lotker, Merav Parter and David Peleg. The Minimum Principle of SINR: A Useful Discretization Tool for Wireless Communication. 56th Annual IEEE Symposium on Foundations of Computer Science (FOCS 2015), Berkeley, CA, October 2015.

[14] Erez Kantor, Zvi Lotker, Merav Parter and David Peleg. The Topology of Wireless Communication. To appear in the Journal of the ACM.

1.2 Graph Network Algorithms

The papers in this section assume an abstract graph network model. Paper [15] shows how one could run many distributed algorithms in the same network with minimal interference. Papers [16]

and [17] provide new algorithms for distributed max flow and single-source reachability. Paper [18] gives a breakthrough result, on computing a Maximal Independent Set much more efficiently than was previously possible. It uses novel feedback-based techniques.

[15] Mohsen Ghaffari. Near-Optimal Scheduling of Distributed Algorithms. ACM Symposium on Principles of Distributed Computing (PODC 2015), Donostia-San Sebastian, Spain, pages 3-12, July 2015. Best Student Paper Award at PODC'15.

[16] Mohsen Ghaffari, Andreas Karrenbauer, Fabian Kuhn, and Christoph Lenzen. Near-Optimal Distributed Maximum Flow. ACM Symposium on Principles of Distributed Computing (PODC 2015), Donostia-San Sebastian, Spain, pages 81-90, July 2015.

[17] Mohsen Ghaffari and Rajan Udwani. Brief Announcement: Distributed Single-Source Reachability. ACM Symposium on Principles of Distributed Computing (PODC 2015), Donostia-San Sebastian, Spain, pages 163-165, July 2015.

[18] Mohsen Ghaffari. An Improved Distributed Algorithm for Maximal Independent Set. ACM-SIAM Symposium on Discrete Algorithms (SODA 2016), Arlington, VA, January 2016. Best Paper Award and Best Student Paper Award. Preprint arXiv:1506.05093v2, 2015.

The next two papers give new and efficient algorithms for a large collection of problems to be solved in planar networks.

[19] Mohsen Ghaffari and Bernhard Haeupler. Distributed Algorithms for Planar Networks I: Planar Embedding. To appear in Proceedings of the ACM Symposium on Principles of Distributed Computing (PODC), Chicago, Illinois, July 2016.

[20] Mohsen Ghaffari and Bernhard Haeupler. Distributed Algorithms for Planar Networks II: Low-Congestion Shortcuts, MST, and Min-Cut. ACM-SIAM Symposium on Discrete Algorithms (SODA 2016), Arlington, VA, January 2016.

Papers [21]-[28] describe a variety of other new and efficient algorithms for communication problems and network structuring problems, in several different types of graph networks.

[21] Mohsen Ghaffari and Merav Parter. Near-Optimal Distributed Algorithms for Fault-Tolerant Tree Structures. To appear in ACM Symposium on Parallelism in Algorithms and Architectures (SPAA), Asilomar State Beach, California, July 2016.

[22] Mohsen Ghaffari and Merav Parter. A Polylogarithmic Gossip Algorithm for Plurality Consensus. To appear in Proceedings of the ACM Symposium on Principles of Distributed Computing (PODC), Chicago, Illinois, July 2016.

[23] Mohsen Ghaffari and Merav Parter. MST in Log-Star Rounds of Congested Clique. To appear in Proceedings of the ACM Symposium on Principles of Distributed Computing (PODC), Chicago, Illinois, July 2016.

[24] Mohsen Ghaffari, Hsin-Hao Su, and Fabian Kuhn. Generalizing the Congested Clique. Submitted for publication, 2016.

[25] David G. Harris, Johannes Schneider, and Hsin-Hao Su. Distributed (A+1)-coloring in Sublogarithmic Rounds. To appear in Proceedings of the 48th Annual Symposium on the Theory of Computing (STOC 2016), Cambridge, MA, June 2016. http://arxiv.org/pdf/1603.01486v1

[26] Stephan Holzer and Nathan Pinsker. Computing Distances and Shortest Paths in the Congested Clique. 19th International Conference on Principles of Distributed Systems (OPODIS), Rennes, France, December 2015.

[27] Benjamin Dissler, Stephan Holzer and Roger Wattenhofer. Distributed Local Multi-Aggregation and Centrality Approximation. Submitted for publication, 2015. arXiv:1605.06882.

[28] Erez Kantor and Shay Kutten. Optimal competitiveness for the Rectilinear Steiner Arborescence problem. In Magnus M. Halldorsson, Kazuo Iwama, Naoki Kobayashi, and Bettina Speckmann, editors, Automata, Languages, and Programming - 42nd International Colloquium (ICALP 2015) Part II, Kyoto, Japan, July 2015 volume 9135 of Lecture Notes in Computer Science, pages 675-687, 2015. Springer. Also, ArXiv: 1504.08265.

1.3 Distributed Data Management

We have made considerable progress on our work on using erasure coding methods to reduce data storage costs, in a distributed data management system (such as a cloud storage system). This work is mainly funded by AFOSR contract FA9550-14-1-0403. However, it is relevant here because our algorithms could be adapted for use in wireless networks.

Paper [29] is a journal version of our previous paper proposing the general idea of using erasure coding for distributed data management, and presenting initial algorithms. Paper [30] presents simplifications and performance improvements on the algorithms of [29]. Paper [31] describes corresponding lower bound results, and [32] integrates data server repairs.

[29] Viveck R. Cadambe, Nancy Lynch, Muriel Medard, and Peter Musial. A Coded Shared Atomic Memory Algorithm for Message Passing Architectures. To appear in Distributed Computing.

[30] Kishori M Konwar, N. Prakash, Erez Kantor, Muriel Medard, Nancy Lynch, and Alexander A. Schwarzmann. Storage-Optimized Data-Atomic Algorithms for Handling Erasures and Errors in Distributed Storage Systems. 30th IEEE International Parallel & Distributed Processing Symposium (IPDPS), May 2016.

[31] Zhiying Wang, Viveck R. Cadambe and Nancy Lynch. Information-Theoretic Lower Bounds on the Storage Cost of Shared Memory Emulation. To appear in Proceedings of the ACM Symposium on Principles of Distributed Computing (PODC), Chicago, Illinois, July 2016.

[32] Kishori Konwar, Nancy Lynch, Muriel Medard and Prakash Narayana Moorthy. RADON: Repairable Atomic Data Object in Networks. Submitted for publication, 2016.

1.4 Biology-Inspired Distributed Algorithms

Finally, we have several new results about algorithms of the sort that might be used by social insect colonies to solve various problems: searching for resources, deciding upon a new nest, estimation of the density of the colony, and allocating themselves among various tasks. These are relevant to wireless networks because the problems are similar to problems typically solved by wireless networks; however, the platform assumptions are weaker, and the algorithms are simpler, and have pleasant properties of flexibility, robustness, and adaptiveness that are also desirable for wireless networks.

[33] Christoph Lenzen, Nancy Lynch, Calvin Newport, and Tsvetomira Radeva. Searching without Communicating: Tradeoffs Between Performance and Selection Complexity. Submitted for publication, 2016.

[34] Casey O'Brien. Solving ANTS with Loneliness Detection and Constant Memory. Masters of Engineering, Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, MA 02139, September 2015. Charles and Jennifer Johnson MEng Thesis Award winner for 2016 (second place).

[35] Mohsen Ghaffari, Cameron Musco, Tsvetomira Radeva, Nancy Lynch. Distributed House-Hunting in Ant Colonies. ACM Symposium on Principles of Distributed Computing (PODC 2015), Donostia-San Sebastian, Spain, pages 57-66, July 2015.

[36] Cameron Musco, Hsin-Hao Su, and Nancy Lynch. Ant-Inspired Density Estimation via Random Walks. To appear in Proceedings of the ACM Symposium on Principles of Distributed Computing (PODC), Chicago, Illinois, July 2016. Also, extended abstract to appear in the 4th Workshop on Biological Distributed Algorithms, Chicago, IL, July 2016. See http://arxiv.org/abs/1603.02981

[37] Nancy Lynch, Tsvetomira Radeva, and Hsin-Hao Su. Brief Announcement: A Distributed Task Allocation in Ant Colonies. 29th International Symposium on Distributed Computing (DISC 2015), Tokyo, Japan, October 2015.

2 Comprehensive summary of progress for the full contract

This AFOSR project has produced many algorithmic results and some lower-bound results for ad hoc wireless network models, and has also developed abstraction layers that are intended to make it easier to design and analyze algorithms and applications for wireless networks. Since some of the results can be expressed in terms of abstract gaph network models, the project results also include many new graph network algorithms. Other results involve two related topics: distributed data management and biology-inspired distributed algorithms.

The complete list of papers we have produced appears elsewhere in this final report. Here we describe highlights. More detailed descriptions of the work, year by year, appear in our four annual progress reports—the one earlier in this file and the three previous ones.

2.1 Wireless Networks

We have obtained many new and efficient *algorithms for reliable radio network models*, for fundamental problems such as global broadcast [1, 2], computing a Maximal Independent Set [3], establishing network structure for multi-message communication [4], and computing a Breadth-First spanning tree [5]. We have also determined the costs of communication in wireless networks with multiple channels [6].

We have also studied *algorithms for unreliable radio networks*, in which some communication links are inconsistently available. It turns out that many of the same problems are much harder to solve when such links must be taken into account. One early highlight was our results on structuring unreliable networks by computing Maximal Independent Sets and Connected Dominating Sets [7], and we recently developed a new leader-election algorithm for such networks [8]. Most of our other work in this direction was focused on the development of *Abstract MAC layers*, which we discuss next.

An *Abstract MAC layer*, also known as a *Local Broadcast layer*, is a distributed abstraction layer for programming wireless networks, hiding the extreme complexities of wireless communication contention management from application developers and algorithm designers. An Abstract MAC layer provides an abstraction of reliable (and efficient) local broadcast communication. Early in this AFOSR project, we finished a journal paper on how one can use Abstract MAC layers to decompose the design of highly efficient high-level protocols, such as global broadcast protocols [9], for reliable radio networks. Subsequently, we focused on algorithms to implement Abstract MAC layers for unreliable radio networks. We first determined some general upper and lower bounds for global and local broadcast in unreliable networks [10]. Most of the results in that paper were negative (lower bounds), but we did obtain interesting preliminary positive results for settings with reasonable schedulers and reasonable geometric constraints. Later, in [11, 12], we built upon these positive results to obtain a new, efficient algorithm to implement an Abstract MAC layer for unreliable radio networks with similar constraints. A highlight of this work is that *efficiency is assessed in terms of local parameters only.*

In other work on Abstract MAC layers, we developed a new, efficient algorithm to implement multi-message broadcast above such a layer [13]. We also designed an interesting algorithm to implement an Abstract MAC layer for reliable *Signal-to-Noise-and-Interference (SINR)* wireless platforms [14]. Once again, efficiency is assessed in terms of local parameters only.

In other work on SINR models, we have designed slgorithms for several problems, including k-selection and sorting, as well as distance computation and information dissemination [15]. Also, we have several results that characterize communication patterns for SINR wireless models [16, 17, 18]. In very recent work [19], we have obtained a new algorithm for fault-tolerant leader election in the SINR model.

We have also been studying algorithms for the *Beeping model*, a very primitive wireless communication model in which wireless nodes can communicate only with special *beep*, not detailed messages. In each round, a node can only detect whether or not at least one of its neighbors has beeped. Early in the project, we showed how one can use the Beeping model to compute a Maximal Independent Set [20]. Very recently, we have been developing an extremely efficient new algorithm for computing a Maximal Independent Set; paper [21] is a preliminary announcement of some of our claims.

In other work, we have developed some interesting new techniques for solving local and global communication problems over wireless networks that support network coding [22, 23, 24]; this work has mainly been supported by NSF Grant number CCF-1217506. Our other work on wireless networks includes [25, 26].

2.2 Graph Networks

During the course of this project, we recognized that many of the ideas we wanted to develop for wireless networks could in fact be expressed in terms of more abstract, simpler graph network models such as the commonly-studied LOCAL and CONGEST models. Expressing them in this way has served to make the work accessible to a broader theoretical audience, and has helped the work to win several Best Paper and Best Student Paper awards. Our earliest work here was a collection of algorithms for routing and leader election in *dynamic graph networks* [27]. The rest of our subsequent work on this topic has been for static networks.

Quite a few of our graph-network algorithms solve *connectivity problems* for the network graphs. For example, we have devised distributed algorithms for determining minimum edge cut approximations [28]; this paper won a Best Paper award for DISC 2013. Our later work on determining vertex connectivity properties [29, 30, 31] has resulted in a Best Student Paper award for PODC 2014. Another batch of graph-network results are for *computing distances and determining optimal graph embeddings* [32, 33, 34, 35, 36]; this has resulted in a Best Student Paper award for ICALP 2014.

We have obtained a notable graph-network algorithm for computing a *Maximal Independent Set* much more efficiently than was previously possible [37]. This algorithm uses a novel feedback-based technique. Our paper won both a Best Paper and a Best Student Paper award for SODA 2016.

This algorithm is easily adapted to the wireless setting; in fact, we built strongly upon this work in designing our Beep-based MIS algorithm, described above.

We have produced many other algorithmic results for traditional graph problems, including computing nearly-optimal maximum flows [38], determining single-source reachability [39], graph coloring [40], and computing a Minumum Spanning Tree [41]. We also have algorithms for fault-tolerant tree structures [42]. For the special case of planar network graphs, we have a comprehensive collection of algorithmic results about planar embedding and other graph problems [43, 44].

Going beyond purely graph-theoretic problems, we have a recent algorithm for solving *plurality consensus* [45]. Finally, we have a very interesting algorithm for scheduling many distributed algorithms to run concurrently, in the same graph-based network, with minimal interference [46]. This work won the Best Student Paper award at PODC 2015.

2.3 Other Topics

The project has also yielded new algorithms for efficient, coherent, faut-tolerant data management in distributed systems, using erasure coding techniques. This work includes papers that present the basic idea of using erasure coding for fault-tolerant distributed data storage and some preliminary data- management algorithms, and later papers that present simpler and more efficient algorithms. We also have new algorithms that integrate server repair into the algorithms, and new information-theoretic lower bounds for the achievable costs of distributed data management [47, 48, 49, 50, 51, 52, 53, 54, 55, 56]. We note that this body of work is primarily funded by AFOSR contract FA9550-14-1-0403, but we mention it here because coherent distributed data management is of interest for wireless networks, and some of our algorithms should carry over to the wireless setting.

Finally, we also studied algorithms that explain the behavior of biological systems. Specifically, we developed and analyzed algorithms of the sort that might be used by social insect colonies to solve typical problems: searching for resources, deciding upon a new nest, estimating the density of the colony, and allocating the members of the colony among various tasks. These algorithms are relevant to wireless networks because the problems are similar to problems typically solved by wireless networks; however, the platform assumptions are weaker, and the algorithms are simpler, and have pleasant properties of flexibility, robustness, and adaptiveness that are also desirable for wireless networks. Contributions here include [57, 58, 59, 60, 61, 62, 63].

2.4 Current Status

It should be evident that, during the time of this AFOSR contract, we have made a great deal of progress in developing a general theory of wireless networks. We have developed numerous new algorithms for several reasonable models for wireless platforms, using a variety of new algorithm design methods. We have developed one important abstraction layer (the Abstract MAC layer) in depth. We have developed many algorithms using a graph network model, which can be transformed to run on wireless networks via general simulations. We have also developed other ways of

decomposing the process of designing wireless network algorithms, for example, by running several algorithms concurrently with low overhead. We have studied the impact of such aspects as unreliable links, scheduling methods, and geographical assumptions on the costs of solving problems. We have moved toward local analysis of algorithms.

Our work is not yet done. Most notably, most of our results have been developed for static networks; it is important to extend many of them to dynamic networks. We would also like to explore more biology-inspired algorithms, with the idea that these might be simpler than typical wireless algorithms, use weaker model assumptions, and also be more flexible to run in different environments, more robust to failures, and more adaptive to changes.

[1] Mohsen Ghaffari, Bernhard Haeupler, and Majid Khabbazian. Randomized broadcast in radio networks with collision detection. In *Proceedings of the 32nd Annual ACM Symposium on Principles of Distributed Computing (PODC'13)*, pages 325–334, Montreal Canada, July 2013.

[2] Noga Alon, Mohsen Ghaffari, Bernhard Haeupler, and Majid Khabbazian. Broadcast throughput in radio networks: Routing vs. network coding. In *Proceedings of the ACM-SIAM Symposium on Discrete Algorithms (SODA 2014)*, pages 1831–1843, Portland, Oregon, January 2014.

[3] Sebastian Daum, Mohsen Ghaffari, Seth Gilbert, Fabian Kuhn, and Calvin Newport. Maximal independent sets in multichannel radio networks. In *Proceedings of the 32nd Annual ACM Symposium on Principles of Distributed Computing (PODC'13)*, pages 335–344, Montreal Canada, July 2013.

[4] Mohsen Ghaffari and Bernard Haeupler. Fast structuring of radio networks for multi-message communications. In Yehuda Afek, editor, *27th International Symposium on DIStributed Computing (DISC'13), Jerusalem, Israel, October 2013*, volume 8205 of *Lecture Notes in Computer Science*, pages 492–506. Springer, 2013.

[5] Mohsen Ghaffari and Bernhard Haeupler. Brief Announcement: Near-optimal BFS computation in radio networks. In *Proceedings of the 33nd Annual ACM Symposium on Principles of Distributed Computing (PODC'14)*, Paris, France, July 2014.

[6] Stephan Holzer, Thomas Locher, Yvonne Anne Pignolet, and Roger Wattenhofer. Deterministic multi-channel information exchange, 2014. Submitted for journal publication.

[7] Keren Censor-Hillel, Seth Gilbert, Fabian Kuhn, Nancy Lynch, and Calvin Newport. Structuring unreliable radio networks. *Distributed Computing*, 27(1):1–19, 2014.

[8] Mohsen Ghaffari and Calvin Newport. Leader election in unreliable radio networks. In *International Colloquium on Automata, Languages, and Programming (ICALP)*, Rome Italy, July 2016. To appear.

[9] Majid Khabbazian, Dariusz Kowalski, Fabian Kuhn, and Nancy Lynch. Decomposing broadcast algorithms using Abstract MAC layers. *Ad-Hoc Networks*, 12:219–242, 2014.

[10] Mohsen Ghaffari, Nancy Lynch, and Calvin Newport. The cost of radio network broadcast for different models of unreliable links. In *Proceedings of the 32nd Annual ACM Symposium on Principles of Distributed Computing*, pages 345–354, Montreal, Canada, July 2013.

[11] Nancy Lynch and Calvin Newport. A (truly) local broadcast layer for unreliable radio networks. Technical Report MIT-CSAIL-TR-2015-016, Computer Science and Artificial Intelligence Laboratory, Massachusetts Institute of Technology, Cambridge, MA 02139, May 2015.

[12] Nancy Lynch and Calvin Newport. A (truly) local broadcast layer for unreliable radio networks. In *Proceedings of the ACM Symposium on Principles of Distributed Computing (PODC 2015)*, pages 109–118, Donostia-San Sebastian, Spain, July 2015.

[13] Mohsen Ghaffari, Erez Kantor, Nancy A. Lynch, and Calvin C. Newport. Multi-message broadcasting with Abstract MAC layers and unreliable links, 2014. CoRR abs/1405.1671.

[14] Magnus Halldorsson, Stephan Holzer, and Nancy Lynch. A local broadcast layer for the SINR network model. In *Proceedings of the ACM Symposium on Principles of Distributed Computing (PODC 2015)*, pages 129–138, Donostia-San Sebastian, Spain, July 2015. ArXiV report available at `http://www.arxiv.org/abs/1505.04514.`.

[15] Stephan Holzer, Sebastian Kohler, and Roger Wattenhofer. Brief Announcement: k-selection and sorting in the SINR model. In Fabian Kuhn, editor, *Distributed Computing - 28th International Symposium (DISC'14), Austin, TX, October 2014*, volume 8784 of *Lecture Notes in Computer Science*, page 559. Springer, 2014.

[16] Erez Kantor, Zvi Lotker, Merav Parter, and David Peleg. Nonuniform sINR+Voronoi diagrams are effectively uniform. In Yoram Moses, editor, *Distributed Computing - 29th International Symposium (DISC 2015), Tokyo, Japan, October 7-9, 2015*, volume 9363 of *Lecture Notes in Computer Science*, pages 588–601. Springer, 2015.

[17] Erez Kantor, Zvi Lotker, Merav Parter, and David Peleg. The minimum principle of SINR: A useful discretization tool for wireless communication. In *56th Annual IEEE Symposium on Foundations of Computer Science (FOCS 2015)*, Berkeley, CA, October 2015.

[18] Erez Kantor, Zvi Lotker, Merav Parter, and David Peleg. The topology of wireless communication. *Journal of the ACM*, 2016. To appear.

[19] Stephan Holzer and Evangelia Anna Markatou. Brief Announcement - Leader election in the sinr model with stopping failures, 2016. Submitted for publication.

[20] Yehuda Afek, Noga Alon, Ziv Bar-Joseph, Alejandro Cornejo, Bernhard Haeupler, and Fabian Kuhn. Beeping a maximal independent set. *Distributed Computing*, 26(4):195–208, 2013. Special issue for *DISC 2011.*

[21] Stephan Holzer and Nancy Lynch. Brief Announcement - Beeping a maximal independent set fast, 2016. Submitted for publication.

[22] Keren Censor-Hillel, Bernhard Haeupler, Nancy Lynch, and Muriel Medard. Bounded-contention coding for the additive network model. *Distributed Computing*, 28(5):297–308, 2015. ArXiv submission, available at `http://arxiv.org/abs/1208.6125`.

[23] Keren Censor-Hillel, Erez Kantor, Nancy Lynch, and Merav Parter. Computing in additive networks with bounded-information codes, 2016. Submitted for journal publication.

[24] Keren Censor-Hillel, Erez Kantor, Nancy Lynch, and Merav Parter. Computing in additive networks with bounded-information codes. In Yoram Moses, editor, *Distributed Computing - 29th International Symposium (DISC 2015), Tokyo, Japan, October 7-9, 2015*, volume 9363 of *Lecture Notes in Computer Science*, pages 405–419. Springer, 2015.

[25] Alejandro Cornejo, Calvin Newport, Subha Gallakota, Jayanthi Rao, and T.J. Giuli. Prioritized gossip in vehicular networks. *Ad-Hoc Networks*, 11(1):397–409, 2013.

[26] Srikanth Sastry, Tsvetomira Radeva, Jianer Chen, and Jennifer Welch. Reliable networks with unreliable sensors. *Pervasive and Mobile Computing*, 9(2):311–323, 2013.

[27] Tsvetomira Radeva. Properties of link reversal algorithms for routing and leader election. Master's thesis, Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, MA, June 2013.

[28] Mohsen Ghaffari and Fabian Kuhn. Distributed minimum cut approximation. In Yehuda Afek, editor, *27th International Symposium on DIStributed Computing (DISC'13), Jerusalem, Israel, October 2013*, volume 8205 of *Lecture Notes in Computer Science*, pages 1–15. Springer, 2013. Best Paper Award.

[29] Keren Censor-Hillel, Mohsen Ghaffari, and Fabian Kuhn. A new perspective on vertex connectivity. In *Proceedings of the ACM-SIAM Symposium on Discrete Algorithms (SODA 2014)*, pages 546–561, Portland, Oregon, January 2014.

[30] Keren Censor Hillel, Mohsen Ghaffari, and Fabian Kuhn. Distributed connectivity decomposition. In *Proceedings of the 33nd Annual ACM Symposium on Principles of Distributed Computing (PODC'14)*, pages 156–165, Paris, France, July 2014. Best Student Paper Award.

[31] Keren Censor-Hillel, Mohsen Ghaffari, George Giakkoupis, Bernhard Haeupler, and Fabian Kuhn. Tight bounds on vertex connectivity under vertex sampling. In *ACM-SIAM Symposium on Discrete Algorithms (SODA)*, pages 2006–2018, San Diego, CA, January 2015.

[32] Mohsen Ghaffari. Near-optimal distributed approximation of minimum-weight connected dominating set. In Javier Esparza, Pierre Fraigniaud, Thore Husfeldt, and Elias Koutsoupias, editors, *Automata, Languages, and Programming - 41st International Colloqiuim (ICALP'14), Copenhagen, Denmark, July 2014*, volume 8573 of *Lecture Notes in Computer Science*, pages 483–494. Springer, 2014. Best Student Paper Award.

[33] Alexandra Hochuli, Stephan Holzer, and Roger Wattenhofer. Efficient approximation of minimum routing cost trees. In Magnus M. Halldorsson, editor, *Proceedings of the 21st International Colloquium on Structural Information and Communication Complexity (SIROCCO'14), Hida Takayama, Japan, July 2014*, volume 8576 of *Lecture Notes in Computer Science*, pages 121–136. Springer, 2014.

[34] Stephan Holzer, David Peleg, Liam Roditty, and Roger Wattenhofer. Brief Announcement: Distributed 3/2-approximation of the diameter. In Fabian Kuhn, editor, *Distributed Computing - 28th International Symposium (DISC'14), Austin, TX, October 2014*, volume 8784 of *Lecture Notes in Computer Science*, page 562. Springer, 2014.

[35] Mohsen Ghaffari and Christoph Lenzen. Near-optimal distributed tree embedding. In Fabian Kuhn, editor, *Distributed Computing - 28th International Symposium (DISC'14), Austin, TX, October, 2014*, volume 8784 of *Lecture Notes in Computer Science*, pages 197–211. Springer, 2014.

[36] Stephan Holzer and Nathan Pinsker. Computing distances and shortest paths in the congested clique. In *19th International Conference on Principles of Distributed Systems (OPODIS)*, Rennes, France, December 2015.

[37] Mohsen Ghaffari. An improved distributed algorithm for maximal independent set. In *ACM-SIAM Symposium on Discrete Algorithms (SODA 2016)*, Arlington, VA, January 2016. Best Paper Award and Best Student Paper Award. Preprint arXiv:1506.05093v2, 2015. `href="http://arxiv.org/pdf/1506.05093v2.pdf`.

[38] Mohsen Ghaffari, Andreas Karrenbauer, Fabian Kuhn, and Christoph Lenzen. Near-optimal distributed maximum flow. In *Proceedings of the ACM Symposium on Principles of Distributed Computing (PODC 2015)*, pages 81–90, Donostia-San Sebastian, Spain, July 2015.

[39] Mohsen Ghaffari and Rajan Udwani. Brief Announcement: Distributed single-source reachability. In *Proceedings of the ACM Symposium on Principles of Distributed Computing (PODC 2015)*, pages 163–165, Donostia-San Sebastian, Spain, July 2015.

[40] David G. Harris, Johannes Schneider, and Hsin-Hao Su. Distributed $((\Delta) + 1)$-coloring in sublogarithmic rounds. In *Proceedings 48th Annual ACM Symposium on Theory of Computing*, 2016. To appear. Also, `http://arxiv.org/pdf/1603.01486v1`.

[41] Mohsen Ghaffari and Merav Parter. MST in log-star rounds of congested clique. In *Proceedings of the ACM Symposium on Principles of Distributed Computing (PODC)*, Chicago, Illinois, July 2016. To appear.

[42] Mohsen Ghaffari and Merav Parter. Near-optimal distributed algorithms for fault-tolerant tree structures. In *ACM Symposium on Parallelism in Algorithms and Architectures (SPAA)*, Asilomar State Beach, California, July 2016. To appear.

[43] Mohsen Ghaffari and Bernhard Haeupler. Distributed algorithms for planar networks i: Planar embedding. In *Proceedings of the ACM Symposium on Principles of Distributed Computing (PODC)*, Chicago, Illinois, July 2016. To appear.

[44] Mohsen Ghaffari and Bernhard Haeupler. Distributed algorithms for planar networks ii: Low-congestion shortcuts, mst, and min-cut. In *ACM-SIAM Symposium on Discrete Algorithms (SODA 2016)*, Arlington, VA, January 2016.

[45] Mohsen Ghaffari and Merav Parter. A polylogarithmic gossip algorithm for plurality consensus. In *Proceedings of the ACM Symposium on Principles of Distributed Computing (PODC)*, Chicago, Illinois, July 2016. To appear.

[46] Mohsen Ghaffari. Near-optimal scheduling of distributed algorithms. In *Proceedings of the ACM Symposium on Principles of Distributed Computing (PODC 2015)*, pages 3–12, Donostia-San Sebastian, Spain, July 2015. Best Student Paper Award at PODC'15.

[47] Viveck Cadambe, Nancy, Lynch, Muriel Médard, and Peter Musial. A coded shared atomic memory algorithm for message passing architectures. *Distributed Computing*, 2016. To appear.

[48] Zhiying Wang, Viveck R. Cadambe, and Nancy Lynch. Information-theoretic lower bounds on the storage cost of shared memory emulation. In *Proceedings of the ACM Symposium on Principles of Distributed Computing (PODC)*, Chicago, Illinois, July 2016. To appear.

[49] Zhiying Wang and Viveck R. Cadambe. Multi-version coding - an information theoretic perspective of consistent distributed storage, 2015. Report on arxiv.org, available online at `http://arxiv.org/abs/1506.00684.`.

[50] Viveck Cadambe, Nancy, Lynch, Muriel Médard, and Peter Musial. A coded shared atomic memory algorithm for message passing architectures. In *13th IEEE International Symposium on Network Computing and Applications (IEEE NCA14)*, pages 253–260, Cambridge, MA, August 2014. Best Paper Award.

[51] Viveck R. Cadambe, Nancy Lynch, Muriel Medard, and Peter Musial. A coded shared atomic memory algorithm for message passing architectures. Technical Report MIT-CSAIL-TR-2014-015, Computer Science and Artificial Intelligence Laboratory, Massachusetts Institute of Technology, Cambridge, MA 02139, August 2014. Also available as arXiv:1407.4167, July 2014.

[52] Zhiying Wang and Viveck Cadambe. On multi-version coding for distributed storage. In *Proceedings of the 52nd Annual Allerton Conference on Communication, Control and Computing*, pages 569–575, Monticello, IL, October 2014.

[53] Zhiying Wang and Viveck Cadambe. Multi-version coding in distributed storage. In *Proceedings of 2014 IEEE International Symposium on Information Theory (ISIT)*, pages 871–875, Honolulu, USA, June 2014.

[54] Viveck R. Cadambe, Nancy Lynch, Muriel Medard, and Peter Musial. Coded emulation of shared atomic memory for message passage architectures. Technical Report MIT-CSAIL-TR-2013-016, Computer Science and Artificial Intelligence Laboratory, Massachusetts Institute of Technology, Cambridge, MA 02139, 2013. Also, submitted for publication.

[55] Kishori Konwar, Nancy Lynch, Muriel Medard, and Prakash Narayana Moorthy. RADON: Repairable atomic data object in networks, 2016. Submitted for publication.

[56] Kishori M Konwar, N. Prakash, Erez Kantor, Muriel Medard, Nancy Lynch, and Alexander A. Schwarzmann. Storage-optimized data-atomic algorithms for handling erasures and errors in distributed storage systems. In *30th IEEE International Parallel & Distributed Processing Symposium (IPDPS)*, Chicago, Illinois, May 2016.

[57] Cameron Musco, Hsin-Hao Su, and Nancy Lynch. Ant-inspired density estimation via random walks. In *Proceedings of the ACM Symposium on Principles of Distributed Computing (PODC)*, Chicago, Illinois, July 2016. To appear. Also, [58]. See `http://arxiv.org/abs/1603.02981`.

[58] Cameron Musco, Hsin-Hao Su, and Nancy Lynch. Ant-inspired density estimation via random walks (extended abstract). In *4th Workshop on Biological Distributed Algorithms*, Chicago, IL, July 2016. To appear.

[59] Mohsen Ghaffari, Cameron Musco, Tsvetomira Radeva, and Nancy Lynch. Distributed house-hunting in ant colonies. In *Proceedings of the ACM Symposium on Principles of Distributed Computing (PODC 2015)*, pages 57–66, Donostia-San Sebastian, Spain, July 2015. Also, arXIV:1505.03799.

[60] Nancy Lynch, Tsvetomira Radeva, and Hsin-Hao Su. Brief Announcement: A distributed task allocation in ant colonies. In *Proceedings of the 29th International Symposium on Distributed Computing (DISC 2015)*, Tokyo, Japan, October 2015.

[61] Christoph Lenzen and Tsvetomira Radeva. The power of phermones in ant foraging. In *1st Workshop on Biological Distributed Algorithms (BDA)*, Jerusalem, Israel, October 2013.

[62] Alejandro Cornejo, Anna Dornhaus, Nancy Lynch, and Radhika Nagpal. Task allocation in ant colonies. In Fabian Kuhn, editor, *Distributed Computing: 28th International Symposium on Distributed Computing (DISC'14), Austin, TX, October 2014*, volume 8784 of *Lecture Notes in Computer Science*, pages 46–60. Springer, 2014.

[63] Casey O'Brien. Solving ANTS with loneliness detection and constant memory, September 2015. Masters of Engineering, Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, MA 02139. Charles and Jennifer Johnson MEng Thesis Award winner for 2016 (second place).

1.

1. Report Type

Final Report

Primary Contact E-mail
Contact email if there is a problem with the report.

lynch@csail.mit.edu

Primary Contact Phone Number
Contact phone number if there is a problem with the report

617-253-7225

Organization / Institution name

MIT

Grant/Contract Title
The full title of the funded effort.

A Comprehensive Theory of Algorithms for Wireless Networks and Mobile Systems

Grant/Contract Number
AFOSR assigned control number. It must begin with "FA9550" or "F49620" or "FA2386".

FA9550-13-1-0042

Principal Investigator Name
The full name of the principal investigator on the grant or contract.

Nancy Lynch

Program Manager
The AFOSR Program Manager currently assigned to the award

Kathleen Kaplan

Reporting Period Start Date

04/01/2013

Reporting Period End Date

05/31/2016

Abstract

This project has produced many new algorithms and some lower-bound results for ad hoc wireless network models, and has also developed abstraction layers that are intended to make it easier to design algorithms and applications for wireless networks. Since some of the results can be expressed in terms of abstract graph networks, the project has also produced many new graph network algorithms. Other results involve distributed data management and biology-inspired distributed algorithms.

More specifically, the project has produced efficient algorithms for both reliable and unreliable radio network wireless platform models, for the rudimentary Beeping model, and for the Signal-to-Noise-and-Interference (SINR) model. These algorithms have solved such problems as local and global broadcast, computing a Maximal Independent Set, and establishing other network structures. The project has developed an Abstract MAC (Local Broadcast) abstraction layer, with efficient implementations over several different wireless platform models, based on reasonable constraints on network geometry.

The project has also produced new graph network algorithms for graph connectivity problems, distance computations, coloring, Maximal Independent Set, and various forms of spanning trees. Finally, it has produced an interesting method for running several distributed algorithms concurrently, in the same graph-

based network. This work
has resulted in six Best Paper and Best Student Paper awards.

Distribution Statement

This is block 12 on the SF298 form.

Distribution A - Approved for Public Release

Explanation for Distribution Statement

If this is not approved for public release, please provide a short explanation. E.g., contains proprietary information.

SF298 Form

Please attach your SF298 form. A blank SF298 can be found here. Please do not password protect or secure the PDF

The maximum file size for an SF298 is 50MB.

sf298.pdf

Upload the Report Document. File must be a PDF. Please do not password protect or secure the PDF . The maximum file size for the Report Document is 50MB.

report.pdf

Upload a Report Document, if any. The maximum file size for the Report Document is 50MB.

Archival Publications (published) during reporting period:

Submitted for Publication

Keren Censor-Hillel, Erez Kantor, Nancy Lynch, and Merav Parter. Computing in additive networks with bounded information codes, 2016. Submitted for journal publication.

Benjamin Dissler, Stephan Holzer, and Roger Wattenhofer. Distributed local multi-aggregation and centrality approximation, 2016. Submitted for publication. Preprint arXiv:1605.06882.

Mohsen Ghaffari, Hsin-Hao Su, and Fabian Kuhn. Generalizing the congested clique, 2016. Submitted for publication.

Magnus Halldorsson, Stephan Holzer, Pradipta Mitra, and Roger Wattenhofer. The power of oblivious wireless power, 2015. Submitted for journal publication.

Stephan Holzer, Thomas Locher, Yvonne Anne Pignolet, and Roger Wattenhofer. Deterministic multi-channel information exchange, 2014. Submitted for journal publication.

Stephan Holzer and Nancy Lynch. Brief Announcement - Beeping a maximal independent set fast, 2016. Submitted for publication.

Stephan Holzer and Evangelia Anna Markatou. Brief Announcement - Leader election in the SINR model with stopping failures, 2016. Submitted for publication.

Kishori Konwar, Nancy Lynch, Muriel Medard, and Prakash Narayana Moorthy. RADON: Repairable atomic data object in networks, 2016. Submitted for publication.

Christoph Lenzen, Nancy Lynch, Calvin Newport, and Tsvetomira Radeva. Searching without communicating: Tradeoffs between performance and selection complexity, 2016. Submitted for publication.

To Appear

Viveck Cadambe, Nancy, Lynch, Muriel Medard, and Peter Musial. A coded shared atomic memory algorithm for message passing architectures. Distributed Computing, 2016. To appear.

Mohsen Ghaffari and Calvin Newport. Leader election in unreliable radio networks. In International Colloquium on Automata, Languages, and Programming (ICALP), Rome Italy, July 2016. To appear.

Mohsen Ghaffari and Bernhard Haeupler. Distributed algorithms for planar networks i: Planar embedding. In Proceedings of the ACM Symposium on Principles of Distributed Computing (PODC), Chicago, Illinois, July 2016. To appear.

Mohsen Ghaffari and Merav Parter. Near-optimal distributed algorithms for fault-tolerant tree structures. In ACM Symposium on Parallelism in Algorithms and Architectures (SPAA), Asilomar State Beach, California, July 2016. To appear.

Mohsen Ghaffari and Merav Parter. A polylogarithmic gossip algorithm for plurality consensus. In Proceedings of the ACM Symposium on Principles of Distributed Computing (PODC), Chicago, Illinois, July 2016. To appear.

Mohsen Ghaffari and Merav Parter. MST in log-star rounds of congested clique. In Proceedings of the ACM Symposium on Principles of Distributed Computing (PODC), Chicago, Illinois, July 2016. To appear.

David G. Harris, Johannes Schneider, and Hsin-Hao Su. Distributed ((Delta)+1)-coloring in sublogarithmic rounds. In Proceedings 48th Annual ACM Symposium on Theory of Computing, 2016. To appear. Also, http://arxiv.org/pdf/1603.01486v1.

Erez Kantor, Zvi Lotker, Merav Parter, and David Peleg. The topology of wireless communication. Journal of the ACM, 2016. To appear.

Erez Kantor and David Peleg. Efficient k-shot broadcasting in radio networks. Journal of Discrete Applied Mathematics, 2016. To appear.

Christoph Lenzen and Roger Wattenhofer. Tight bounds for parallel randomized load balancing. Distributed Computing, 2016. To appear.

Cameron Musco, Hsin-Hao Su, and Nancy Lynch. Ant-inspired density estimation via random walks. In Proceedings of the ACM Symposium on Principles of Distributed Computing (PODC), Chicago, Illinois, July 2016. To appear. See http://arxiv.org/abs/1603.02981.

Cameron Musco, Hsin-Hao Su, and Nancy Lynch. Ant-inspired density estimation via random walks (extended abstract). In 4th Workshop on Biological Distributed Algorithms, Chicago, IL, July 2016. To appear.

Zhiying Wang, Viveck R. Cadambe, and Nancy Lynch.
Information-theoretic lower bounds on the storage cost of shared memory emulation. In Proceedings of the ACM Symposium on Principles
of Distributed Computing (PODC), Chicago, Illinois, July 2016. To appear.

2016

Mohsen Ghaffari. An improved distributed algorithm for maximal independent set. In ACM-SIAM Symposium on Discrete Algorithms (SODA 2016), Arlington, VA, January 2016. Best Paper Award and Best Student Paper Award. Preprint arXiv:1506.05093v2, 2015.

Mohsen Ghaffari and Bernhard Haeupler. Distributed algorithms for planar networks II: Low-congestion shortcuts, MST, and min-cut. In ACM-SIAM Symposium on Discrete Algorithms (SODA 2016), Arlington, VA,

January 2016.

Kishori M Konwar, N. Prakash, Erez Kantor, Muriel Medard, Nancy Lynch, and Alexander A. Schwarzmann. Storage-optimized data-atomic algorithms for handling erasures and errors in distributed storage systems. In 30th IEEE International Parallel & Distributed Processing Symposium (IPDPS), Chicago, Illinois, May 2016.

2015

Keren Censor-Hillel, Erez Kantor, Nancy Lynch, and Merav Parter. Computing in additive networks with bounded-information codes. In Yoram Moses, editor, Distributed Computing - 29th International Symposium (DISC 2015), Tokyo, Japan, October 7-9, 2015, volume 9363 of Lecture Notes in Computer Science, pages 405--419. Springer, 2015.

Keren Censor-Hillel, Bernhard Haeupler, Nancy Lynch, and Muriel Medard. Bounded-contention coding for the additive network model. Distributed Computing, 28(5):297--308, 2015. ArXiv submission, available at http://arxiv.org/abs/1208.6125.

Keren Censor-Hillel, Mohsen Ghaffari, George Giakkoupis, Bernhard Haeupler, and Fabian Kuhn. Tight bounds on vertex connectivity under vertex sampling. In ACM-SIAM Symposium on Discrete Algorithms (SODA), pages 2006--2018, San Diego, CA, January 2015.

Mohsen Ghaffari, Cameron Musco, Tsvetomira Radeva, and Nancy Lynch. Distributed house-hunting in ant colonies. In Proceedings of the ACM Symposium on Principles of Distributed Computing (PODC 2015), pages 57--66, Donostia-San Sebastian, Spain, July 2015. Also, arXIV:1505.03799.

Mohsen Ghaffari. Near-optimal scheduling of distributed algorithms. In Proceedings of the ACM Symposium on Principles of Distributed Computing (PODC 2015), pages 3--12, Donostia-San Sebastian, Spain, July 2015. Best Student Paper Award at PODC'15.

Mohsen Ghaffari, Andreas Karrenbauer, Fabian Kuhn, and Christoph Lenzen. Near-optimal distributed maximum flow. In Proceedings of the ACM Symposium on Principles of Distributed Computing (PODC 2015), pages 81--90, Donostia-San Sebastian, Spain, July 2015.

Mohsen Ghaffari and Rajan Udwani. Brief Announcement: Distributed single-source reachability. In Proceedings of the ACM Symposium on Principles of Distributed Computing (PODC 2015), pages 163--165, Donostia-San Sebastian, Spain, July 2015.

Magnus Halldorsson, Stephan Holzer, and Nancy Lynch. A local broadcast layer for the SINR network model. In Proceedings of the ACM Symposium on Principles of Distributed Computing (PODC 2015), pages 129--138, Donostia-San Sebastian, Spain, July 2015. ArXiV report available at http://www.arxiv.org/abs/1505.04514.

Stephan Holzer and Nathan Pinsker. Computing distances and shortest paths in the congested clique. In 19th International Conference on Principles of Distributed Systems (OPODIS), Rennes, France, December 2015.

Stephan Holzer and Nathan Pinsker. Poster: Computing distances and shortest paths in the congested clique. In Distributed Computing: 29th International Symposium (DISC 2015), Tokyo, Japan, October 2015.

Erez Kantor, Zvi Lotker, Merav Parter, and David Peleg. Nonuniform SINR+Voronoi diagrams are effectively uniform. In Yoram Moses, editor, Distributed Computing - 29th International Symposium (DISC

2015), Tokyo, Japan, October 7-9, 2015, volume 9363 of Lecture Notes in Computer Science, pages 588--601. Springer, 2015.

Majid Khabbazian. Near-optimal multi-version codes. In Proceedings of the 53rd Annual Allerton Conference on Communication, Control and Computing, October 2015.

Erez Kantor, Zvi Lotker, Merav Parter, and David Peleg. The minimum principle of SINR: A useful discretization tool for wireless communication. In 56th Annual IEEE Symposium on Foundations of Computer Science (FOCS 2015), Berkeley, CA, October 2015.

Nancy Lynch, Tsvetomira Radeva, and Hsin-Hao Su. Brief Announcement: A distributed task allocation in ant colonies. In Proceedings of the 29th International Symposium on Distributed Computing (DISC 2015), Tokyo, Japan, October 2015.

Nancy Lynch and Calvin Newport. A (truly) local broadcast layer for unreliable radio networks. In Proceedings of the ACM Symposium on Principles of Distributed Computing (PODC 2015), pages 109--118, Donostia-San Sebastian, Spain, July 2015.

Nancy Lynch and Calvin Newport. A (truly) local broadcast layer for unreliable radio networks. Technical Report MIT-CSAIL-TR-2015-016, Computer Science and Artificial Intelligence Laboratory, Massachusetts Institute of Technology, Cambridge, MA 02139, May 2015.

Casey O'Brien. Solving ANTS with loneliness detection and constant memory, September 2015. Masters of Engineering, Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, MA 02139. Charles and Jennifer Johnson MEng Thesis Award winner for 2016 (second place).

Zhiying Wang and Viveck R. Cadambe. Multi-version coding - an information theoretic perspective of consistent distributed storage, 2015. Report on arxiv.org, available online at http://arxiv.org/abs/1506.00684.

2014

Erez Kantor and Shay Kutten. Optimal competitiveness for symmetric rectilinear steiner arborescence and related problems. In Javier Esparza, Pierre Fraigniaud, Thore Husfeldt, and Elias Koutsoupias, editors, Automata, Languages, and Programming - 41st International Colloquium (ICALP'14), Copenhagen, Denmark, July, 2014, volume 8573 of Lecture Notes in Computer Science, pages 520--531. Springer, 2014. ArXiv: 1504.08265.

Noga Alon, Mohsen Ghaffari, Bernhard Haeupler, and Majid Khabbazian. Broadcast throughput in radio networks: Routing vs. network coding. In Proceedings of the ACM-SIAM Symposium on Discrete Algorithms (SODA 2014), pages 1831--1843, Portland, Oregon, January 2014.

Giuseppe Bianchi, Lorenzo Bracciale, Keren Censor-Hillel, Andrea Lincoln, and Muriel Medard. The one-out-of-k retrieval problem and linear network coding. In 4th International Castle Meeting on Coding Theory and Applications (ICMCTA 2014), Castle of Palmela, Portugal, September 2014.

Viveck Cadambe, Nancy, Lynch, Muriel Medard, and Peter Musial. A coded shared atomic memory algorithm for message passing architectures. In 13th IEEE International Symposium on Network Computing and Applications (IEEE NCA14), pages 253--260, Cambridge, MA, August 2014. Best Paper Award.

Viveck R. Cadambe, Nancy Lynch, Muriel Medard, and Peter Musial. A coded shared atomic memory

algorithm for message passing architectures. Technical Report MIT-CSAIL-TR-2014-015, Computer Science and Artificial Intelligence Laboratory, Massachusetts Institute of Technology, Cambridge, MA 02139, August 2014. Also available as arXiv:1407.4167, July 2014.

Keren Censor Hillel, Mohsen Ghaffari, and Fabian Kuhn. Distributed connectivity decomposition. In Proceedings of the 33nd Annual ACM Symposium on Principles of Distributed Computing (PODC'14), pages 156--165, Paris, France, July 2014. Best Student Paper Award.

Keren Censor-Hillel, Seth Gilbert, Fabian Kuhn, Nancy Lynch, and Calvin Newport. Structuring unreliable radio networks. Distributed Computing, 27(1):1--19, 2014.

Keren Censor-Hillel, Mohsen Ghaffari, and Fabian Kuhn. A new perspective on vertex connectivity. In Proceedings of the ACM-SIAM Symposium on Discrete Algorithms (SODA 2014), pages 546--561, Portland, Oregon, January 2014.

Hyun Chul Chung, Srikanth Sastry, and Jennifer L. Welch. Stabilizing dining with failure locality 1. In Mainak Chatterjee, Jian-Nong Cao, Kishore Kothapalli, and Sergio Rajsbaum, editors, Distributed Computing and Networking - 15th International Conference (ICDCN 2014), Coimbatore, India, January 2014, volume 8314 of Lecture Notes in Computer Science, pages 532--537, 2014.

Alejandro Cornejo, Anna Dornhaus, Nancy Lynch, and Radhika Nagpal. Task allocation in ant colonies. In Fabian Kuhn, editor, Distributed Computing: 28th International Symposium on Distributed Computing (DISC'14), Austin, TX, October 2014, volume 8784 of Lecture Notes in Computer Science, pages 46--60. Springer, 2014.

Yuval Emek, Stephan Holzer, and Roger Wattenhofer. The power of a leader in the stone age. In 2nd Workshop on Biological Distributed Algorithms (BDA'14), Austin, TX, October 2014.

Mohsen Ghaffari and Bernhard Haeupler. Optimal error rates for interactive coding ii: Efficiency and list decoding. In IEEE Symposium on Foundations of Computer Science (FOCS), pages 394--403, Philadelphia, PA, October 2014.

Mohsen Ghaffari and Christoph Lenzen. Near-optimal distributed tree embedding. In Fabian Kuhn, editor, Distributed Computing - 28th International Symposium (DISC'14), Austin, TX, October, 2014, volume 8784 of Lecture Notes in Computer Science, pages 197--211. Springer, 2014.

Mohsen Ghaffari and Bernhard Haeupler. Brief Announcement: Near-optimal BFS computation in radio networks. In Proceedings of the 33nd Annual ACM Symposium on Principles of Distributed Computing (PODC'14), Paris, France, July 2014.

Mohsen Ghaffari, Bernhard Haeupler, and Madhu Sudan. Optimal error rates for interactive coding I: Adaptivity and other settings. In Proceedings of the 46th Annual Symposium on the Theory of Computing (STOC'14), pages 794--803, New York, NY, May 31-June 3 2014.

Mohsen Ghaffari, Erez Kantor, Nancy Lynch, and Calvin Newport. Multi-message broadcast with Abstract MAC layers and unreliable links. In Proceedings of the 33nd Annual ACM Symposium on Principles of Distributed Computing (PODC'14), pages 56--65, Paris, France, July 2014.

Mohsen Ghaffari, Erez Kantor, Nancy A. Lynch, and Calvin C. Newport. Multi-message broadcasting with Abstract MAC layers and unreliable links, 2014. CoRR abs/1405.1671.

Mohsen Ghaffari. Near-optimal distributed approximation of

minimum-weight connected dominating set. In Javier Esparza, Pierre Fraigniaud, Thore Husfeldt, and Elias Koutsoupias, editors, Automata, Languages, and Programming - 41st International Colloqiuim (ICALP'14), Copenhagen, Denmark, July 2014, volume 8573 of Lecture Notes in Computer Science, pages 483--494. Springer, 2014. Best Student Paper Award.

Miikka Hilke, Christoph Lenzen, and Jukka Suomela. Brief Announcement: Local approximability of minimum dominating set on planar graphs. In Proceedings of the 33nd Annual ACM Symposium on Principles of Distributed Computing (PODC'14), pages 344--346, Paris, France, July 2014.

Alexandra Hochuli, Stephan Holzer, and Roger Wattenhofer. Efficient approximation of minimum routing cost trees. In Magnus M. Halldorsson, editor, Proceedings of the 21st International Colloquium on Structural Information and Communication Complexity (SIROCCO'14), Hida Takayama, Japan, July 2014, volume 8576 of Lecture Notes in Computer Science, pages 121--136. Springer, 2014.

Stephan S. Holzer. Distance Computation, Information Dissemination, and Wireless Capacity in Networks, volume 19 of Series in Distributed Computing. Hartung-Gorre, 2014.

Stephan Holzer, Sebastian Kohler, and Roger Wattenhofer. Brief Announcement: k-selection and sorting in the SINR model. In Fabian Kuhn, editor, Distributed Computing - 28th International Symposium (DISC'14), Austin, TX, October 2014, volume 8784 of Lecture Notes in Computer Science, page 559. Springer, 2014.

Stephan Holzer and Nathan Pinsker. Approximation of distances and shortest paths in the broadcast congest clique, 2014. CoRR abs/1412.3445.

Stephan Holzer, David Peleg, Liam Roditty, and Roger Wattenhofer. Brief Announcement: Distributed 3/2-approximation of the diameter. In Fabian Kuhn, editor, Distributed Computing - 28th International Symposium (DISC'14), Austin, TX, October 2014, volume 8784 of Lecture Notes in Computer Science, page 562. Springer, 2014.

Majid Khabbazian, Dariusz Kowalski, Fabian Kuhn, and Nancy Lynch. Decomposing broadcast algorithms using Abstract MAC layers. Ad-Hoc Networks, 12:219--242, 2014.

Christoph Lenzen and Boaz Patt-Shamir. Improved distributed steiner forest construction. In Proceedings of the 33nd Annual ACM Symposium on Principles of Distributed Computing (PODC'14), pages 262--271, Paris, France, July 2014.

Christoph Lenzen, Nancy Lynch, Calvin Newport, and Tsvetomira Radeva. Trade-offs between selection complexity and performance when searching the plane without communication. In Proceedings of the 33nd Annual ACM Symposium on Principles of Distributed Computing (PODC'14), pages 252--261, Paris, France, July 2014.

Zhiying Wang and Viveck Cadambe. On multi-version coding for distributed storage. In Proceedings of the 52nd Annual Allerton Conference on Communication, Control and Computing, pages 569--575, Monticello, IL, October 2014.

Zhiying Wang and Viveck Cadambe. Multi-version coding in distributed storage. In Proceedings of 2014 IEEE International Symposium on Information Theory (ISIT), pages 871--875, Honolulu, USA, June 2014.

2013

Yehuda Afek, Noga Alon, Ziv Bar-Joseph, Alejandro Cornejo, Bernhard Haeupler, and Fabian Kuhn. Beeping a maximal independent set. Distributed Computing, 26(4):195--208, 2013. Special issue for DISC 2011.

Viveck R. Cadambe, Nancy Lynch, Muriel Medard, and Peter Musial. Coded emulation of shared atomic memory for message passage architectures. Technical Report MIT-CSAIL-TR-2013-016, Computer Science and Artificial Intelligence Laboratory, Massachusetts Institute of Technology, Cambridge, MA 02139, 2013. Also, submitted for publication.

Israel Cidon, Erez Kantor, and Shay Kutten. Prudent opportunistic cognitive radio access protocols. In Yehuda Afek, editor, 27th International Symposium on DIStributed Computing (DISC'13), Jerusalem, Israel, October, 2013, volume 8205 of Lecture Notes in Computer Science, pages 462--476. Springer, 2013.

Alejandro Cornejo, Calvin Newport, Subha Gallakota, Jayanthi Rao, and T.J. Giuli. Prioritized gossip in vehicular networks. Ad-Hoc Networks, 11(1):397--409, 2013.

Sebastian Daum, Mohsen Ghaffari, Seth Gilbert, Fabian Kuhn, and Calvin Newport. Maximal independent sets in multichannel radio networks. In Proceedings of the 32nd Annual ACM Symposium on Principles of Distributed Computing (PODC'13), pages 335--344, Montreal Canada, July 2013.

Danny Dolev, Janne H. Korhonen, Christoph Lenzen, Joel Rybicki, and Jukka Suomela. Synchronous counting and computational algorithm design. In Teruo Higashino, Yoshiaki Katayama, Toshimitsu Masuzawa, Maria Potop-Butucaru, and Masafumi Yamashita, editors, 15th International Symposium on Stabilization, Safety, and Security of Distributed Systems (SSS 2013), Osaka, Japan, November, 2013, volume 8255 of Lecture Notes in Computer Science, pages 237--250. Springer, 2013.

Danny Dolev and Christoph Lenzen. Brief Announcement: Communication-efficient byzantine consensus without a common clock. In Yehuda Afek, editor, 27th International Symposium on DIStributed Computing (DISC'13), Jerusalem Israel, October 2013, volume 8205 of Lecture Notes in Computer Science, page 569, 2013.

Danny Dolev and Christoph Lenzen. Early-deciding consensus is expensive. In Proceedings of the 32nd Annual ACM Symposium on Principles of Distributed Computing, Montreal Canada, July 2013.

Mohsen Ghaffari and Fabian Kuhn. Distributed minimum cut approximation. In Yehuda Afek, editor, 27th International Symposium on DIStributed Computing (DISC'13), Jerusalem, Israel, October 2013, volume 8205 of Lecture Notes in Computer Science, pages 1--15. Springer, 2013. Best Paper Award.

Mohsen Ghaffari, Nancy Lynch, and Calvin Newport. The cost of radio network broadcast for different models of unreliable links. In Proceedings of the 32nd Annual ACM Symposium on Principles of Distributed Computing, pages 345--354, Montreal, Canada, July 2013.

Mohsen Ghaffari, Bernhard Haeupler, and Majid Khabbazian. Randomized broadcast in radio networks with collision detection. In Proceedings of the 32nd Annual ACM Symposium on Principles of Distributed Computing (PODC'13), pages 325--334, Montreal Canada, July 2013.

Mohsen Ghaffari and Bernard Haeupler. Fast structuring of radio networks for multi-message communications. In Yehuda Afek, editor, 27th International Symposium on DIStributed Computing (DISC'13), Jerusalem, Israel, October 2013, volume 8205 of Lecture Notes in Computer Science, pages 492--506. Springer, 2013.

Rebecca Ingram, Tsvetomira Radeva, Patrick Shields, Saira Viqar, Jennifer E. Walter, and Jennifer L. Welch. A leader election algorithm for dynamic networks with causal clocks. Distributed Computing, 26(2):75--97, 2013.

Christoph Lenzen. Optimal deterministic routing, and sorting on the congested clique. In Proceedings of the 32nd Annual ACM Symposium on Principles of Distributed Computing, Montreal Canada, July 2013.

Christoph Lenzen and David Peleg. Efficient distributed source detection with limited bandwidth. In Proceedings of the 32nd Annual ACM Symposium on Principles of Distributed Computing, Montreal Canada, July 2013.

Christoph Lenzen, Yvonne-Anne Pignolet, and Roger Wattenhofer. Distributed minimum dominating set approximations in restricted families of graphs. Distributed Computing, 26(2):119--137, 2013.

Christoph Lenzen and Tsvetomira Radeva. The power of phermones in ant foraging. In 1st Workshop on Biological Distributed Algorithms (BDA), Jerusalem, Israel, October 2013.

Tsvetomira Radeva. Properties of link reversal algorithms for routing and leader election. Master's thesis, Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, MA, June 2013.

Srikanth Sastry, Tsvetomira Radeva, Jianer Chen, and Jennifer Welch. Reliable networks with unreliable sensors. Pervasive and Mobile Computing, 9(2):311--323, 2013.

2. New discoveries, inventions, or patent disclosures:

Do you have any discoveries, inventions, or patent disclosures to report for this period?

No

Please describe and include any notable dates

Do you plan to pursue a claim for personal or organizational intellectual property?

Changes in research objectives (if any):

None

Change in AFOSR Program Manager, if any:

Extensions granted or milestones slipped, if any:

None

AFOSR LRIR Number

LRIR Title

Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, $K)

	Starting FY	FY+1	FY+2
Salary			
Equipment/Facilities			
Supplies			
Total			

Report Document

Report Document - Text Analysis

Report Document - Text Analysis

Appendix Documents

2. Thank You

E-mail user

Jun 08, 2016 13:20:52 Success: Email Sent to: lynch@csail.mit.edu